Aquatic Ecology

Aquaculture Impacts on Estuarine Ecosystems.

Background.

With the decline of the fishing industry and the expansion of aquacultural technology has come an increased interest in managed cultivation of shellfish on Cape Cod. Using natural shellfish habitat to grow seeded shellfish stocks, the Cape's marine aquaculture industry produces substantial harvests of quahogs (*Mercenaria mercenaria*) and Atlantic oysters (*Crassostrea gigas*), as well as small quantities of scallops (*Aequipecten irradians*), soft shell clams (*Mya arenaria*) and blue mussels (*Mytilus edulis*). As interest in the aquacultural use of estuaries and tidal flats within the boundaries of Cape Cod National Seashore increases, so must research on the ecological implications of aquaculture in CACO's estuarine systems.

Research Needs.

Research conducted to date on the ecosystem effects of aquaculture has been limited to studies of effects on sediment and benthic infauna; effects of oyster culture on bird populations have also been minimally addressed, but more comprehensive research is needed to determine the impacts of aquacultural practices on estuarine communities in CACO. The aquaculture "carrying capacity" needs to be determined for each of CACO's farmed areas, and possible long-term impacts to sediment geochemistry and benthic communities need to be more thoroughly explored. The use of intertidal mud flats by other fisheries and by migratory shorebirds in relation to aquaculture operations within CACO should also be investigated, with specific attention to: the selection or avoidance of aquaculture areas by fish (high tide) and migrant shorebirds (low and high tide) during each season; differences in fish and shorebird diversity between open tidal flats and aquaculture areas; temporal and spatial variation of fish and shorebird abundance on open tidal flats and aquaculture areas; and intraseasonal shifts in the use of tidal flats and aquaculture areas as compared with overall abundance changes at specific sites, such as Nauset Marsh and Wellfleet Bay.

(See related project descriptions under "Marsh-Dwelling Shorebirds," in the Wildlife Ecology chapter.)

Coastal Bays and Estuaries.

Background.

Cape Cod's bays and tidal estuaries are among the most biologically productive ecosystems in the world, producing between five and ten tons of organic matter per acre every year. This organic material plays a vital role in the marine food chain of the Northeast Atlantic: the decomposed plant matter that washes into the estuaries from adjacent salt marshes supports algae and plankton, which feed fish, shellfish and insects, which in turn support larger fish, birds, mammals and people. In addition to a number of threatened and endangered plants and animals, it is estimated that two-thirds of the region's commercially important fish and shellfish species spend at least part of their life cycle in an estuary. Seven major marsh and estuarine systems exist within Cape Cod National Seashore, with varying degrees of historic human disturbance and alteration – West End and Hatches Harbor in Provincetown, East Harbor and the Pamet River in Truro, the Herring River in Wellfleet, Pleasant Bay, bordered by the towns of Orleans, Chatham and Harwich, and Nauset Marsh, the most extensive and least disturbed estuary at the seashore, in Eastham.

At CACO and indeed throughout the world, human-induced nitrogen loading is degrading coastal embayments by stimulating massive micro- and macroalgal blooms. Such blooms harm coastal ecosystems by depriving bottom-dwelling plants and animals of the sunlight they need to thrive and by stripping water of oxygen during their decomposition process, creating the potential for massive fish and shellfish kills due to anoxic conditions. Unlike more river-dominated areas, most nitrogen pollution on the Cape enters coastal waters with groundwater from the highly permeable aquifer. Nitrate-nitrogen, primarily from septic wastes, is carried with little attenuation to the shoreline. Although cultural eutrophication of CACO embayments has yet to be demonstrated, groundwater nitrogen values downgradient of developed areas, and immediately upgradient of sensitive surface waters, are often much above normal unpolluted conditions. Upgradient development and sewage disposal continue, with effects that may not reach a critical threshold for some time. Already, however, massive macroalgal blooms occur sporadically in Nauset Marsh and thick epiphytic algal growth suggestive of nutrient excesses occurs on eelgrass in less well-flushed portions of the Nauset system.

A monitoring program was initiated at Nauset Marsh in 1990, as recommended in a Rutgers University study (Roman and Able, 1989). However, this program was discontinued in 1993 due to insufficient funding. Continuation and expansion of this monitoring to include all the estuarine systems at CACO is critically needed for a thorough assessment of the health of, and threats to, outer Cape estuaries.

Coastal Bays and Estuaries, continued.

Research Needs.

Monitor Estuarine Nutrient Enrichment: A protocol for estuarine nutrient enrichment monitoring is currently being developed in partnership with the United States Geological Survey. Upon its completion, monitoring is needed to determine the extent and degree of nitrogen and phosphorous loading into CACO coastal systems via surface runoff and groundwater discharge, and to establish a pattern for such nutrient loading. Ongoing nitrate surveys should be expanded in scope to include ammonium and phosphate, and shoreline surveys should continue to control for high spatial variation, to document seasonal differences and to extend the sampled area. Concurrent studies of macroalgal *Cladophora* production and eelgrass health are required to expose likely indicators of eutrophication. Continuation of this expanded monitoring on a long-term basis is a critical component of local land management and resource protection measures.

Monitor Nekton in Shallow Estuarine Habitats: Because fish and decapod crustaceans are an integral link in the estuarine food web and because they exhibit unique and relatively rapid responses to environmental change, nekton are strong indicators of overall estuarine ecosystem health. As part of CACO's Inventory & Monitoring (I&M) program and in conjunction with the USGS – Water Resources Division, a monitoring protocol has been developed for nekton in shallow subtidal habitats. Long-term monitoring according to this protocol is now needed to address questions related to estuarine habitat restoration and to detect changes, both natural and anthropogenic, in these systems over time.

Monitor Estuarine and Marine Fisheries: Although they are in some cases out of the jurisdiction of the seashore, the health of the outer Cape's marine fisheries is also an important indicator of the condition of CACO's estuarine systems and offshore waters. Research is needed to determine the location and productivity of finfish and shellfish nursery areas at CACO, and the habitat needs and predator-prey interactions of primary fisheries species. Initial investigations should be followed by long-term fisheries monitoring in order to assess changes to CACO's fish populations over time.

Monitor Overall Estuarine Health: Some CACO-wide estuarine monitoring protocols, including salt marsh vegetation, sediment elevation, water quality and the above-mentioned estuarine nutrient enrichment and nekton monitoring, are currently in place or in the process of being developed at CACO for the emerging I&M program. To better understand the dynamic nature of estuaries on the outer Cape and the numerous threats to these systems, however, all aspects of the intensive long-term monitoring program that was initiated for Nauset Marsh in 1990 need to be resumed for all estuarine systems within the park. Investigations of the impacts of adjacent land-use on marine habitats should continue for eelgrass, *Cladophora* and anoxic deep-water zones, and other macroalgae should be sampled at Nauset Marsh to determine changes in species composition since the original Rutgers University report. Specific parameters to be monitored include temperature and salinity, eelgrass wasting disease indices, algae biomass on mudflats and species occurrence in tidal channels.

Coastal Bays and Estuaries, continued.

(See "Estuarine Habitat Restoration" for related project descriptions.)

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Estuarine Habitat Restoration.

Background.

Salt marshes are one of the most productive ecosystems in the world, producing between five and ten tons of organic matter per acre every year. Much of this organic material is not consumed directly by marsh wildlife, but is instead washed into tidal estuaries, where it plays a vital role in the food chain: the decomposed plant matter supports algae and plankton, which feed fish, shellfish, and insects, which in turn support larger fish, birds, mammals and even people – over two-thirds of commercially important fish and shellfish spend at least part of their life cycle in a salt marsh. Marshes also serve as protective barriers during hurricanes and winter storms, absorbing much of the rising seawater and heightened wave energy that would otherwise batter coastal areas, and they protect the health of coastal waters by absorbing nitrogen, which leaks into the water supply from septic systems.

Unfortunately, fifty percent of the nation's coastal wetlands have been destroyed and even more have been significantly impacted by human activity (Roman et al., 1995a). Many of the marshes within Cape Cod National Seashore have been altered by dikes and/or tide gates and subsequently drained. This practice of "marsh reclamation" dates back to the late-1600s and was meant to reduce mosquito populations, increase productive agricultural acreage and improve roadways (Portnoy and Soukup, 1988). Although mosquitoes in many diked areas remain abundant, much native habitat has been lost as a result of the diking.

The National Park Service has been conducting research on tide-restricted areas since 1980 in an effort to document the dramatic alteration of plant and wildlife habitat caused by the restriction of seawater flow into salt marshes (Soukup and Portnoy, 1986; Portnoy and Giblin, 1997). Salt marshes require sediment input from the ocean in order to remain elevated above sea level rise. Dike structures prevent this process from occurring, causing such marshes to be vulnerable to flooding when dikes are breached. Additionally, salt marsh peat left after the marsh is drained periodically releases toxic acids and aluminum as it decomposes, resulting in the potential for massive fish kills (Soukup and Portnoy, 1986). Diking also reduces and sometimes altogether eliminates tidal flushing of nitrogen from salt marsh estuaries, leading to eutrophication and potential oxygen depletion. Constant summertime oxygen stress from lack of tidal flushing reduces both fish and invertebrate numbers and diversity in diked and drained wetlands (Portnoy, 1991).

Estuarine Habitat Restoration, continued.

Restoration of salt marshes provides resource managers with a valuable tool for maintaining and enhancing coastal zone habitat diversity. Numerous studies in other regions have shown that degraded coastal wetlands and small estuaries can be successfully restored, using pre-restoration hydrologic modeling to predict tide height levels and tidal flooding elevations that may occur as a result of restoration (Roman et al., 1995). There are three estuary systems and one coastal lagoon currently in various stages of consideration for tidal flow restoration within CACO: the Herring River in Wellfleet, Hatches Harbor in Provincetown, and the Pamet River and Pilgrim Lake in Truro.

Herring River. The 5-kilometer long Herring River is part of a 405-hectare salt marsh estuary system that has been dramatically altered by humans over the last 150 years. Tidal flow in the Herring River was initially modified by the construction of a railroad through the area in the 1850s and was further reduced in 1908 by a dike built at Chequesset Neck to allow mosquito control drainage and to create arable land. Salt hay and fish production decreased as a result of this dike; the mosquito nuisance, however, did not. Abundant breeding of freshwater and brackish species (*Aedes sollicitans, A. cantator*) continued in the stagnant water behind the structure, leading to extensive ditch drainage of the freshened marshes beginning in 1910 and culminating in the channelization and straightening of the main stream and tributary creeks in the early 1930s. By the late 1960s, the dike had gradually deteriorated, allowing increased tidal flow and re-colonization of oysters and soft shell clams in previously freshened portions of the estuary. This return of shellfish to the area spurred local public support to remove the dike and restore tidal flow to the system. Despite great opposition, however, the original dike was rebuilt in 1975 by the state, this time with specific requirements imposed by the town conservation commission for a minimum amount of tidal flow through an adjustable gate in the structure. These water levels were not achieved until CACO staff demonstrated a shortfall in the dike's operation to the state attorney general's office in 1981. Though present tidal flow approaches those prescribed by the town's Order of Conditions, serious biogeochemical disturbance remains.

Since 1980, CACO has conducted extensive studies of the hydrology, chemistry and biology of the Herring River system. This work was initially prompted by a series of massive kills of alewife (*Alosa pseudoharengus*) and blue-backed herring (*Alosa aestivalis*), anadromous species that annually spawn in the kettle ponds at the river's headwaters. Over the past ten years, CACO has shown that reduced tidal flushing and seawater excursion into the estuary, and increased salt marsh peat oxidation due to drainage, have lead to sulfate oxidation, surface water acidification and, perhaps most seriously, the seasonal oxygen depletion responsible for the massive fish kills in the early 1980s. Cooperating scientists quantified the loss of estuarine habitat due both to reductions in salinity and flooding frequency, and to vegetative shifts from *Spartina* cover to *Phragmites*, freshwater wetland and even upland plant species. Rutgers University researchers modeled the full range of dike opening alternatives and predicted major ecological and social benefits for restored tidal flow.

Estuarine Habitat Restoration, continued.

As mentioned above, dikes were historically constructed in order to reduce and eliminate saltwater mosquito habitats. Studies have found, however, that mosquito populations continue to thrive in the presence of dikes (Portnoy, 1984). Surface water acidification by high sulfate limits fish populations, which are natural predators of mosquitoes, and acid-tolerant mosquitoes are favored in the stagnant waters behind the structures. Based on this information, Portnoy (1984) has predicted that in addition to an increase in typical marsh-estuarine vegetation, a decrease in stream anoxia and acidification and a restoration of fish habitat and shellfish populations, restored tidal flushing will also produce an actual decline in mosquito populations. The restoration of the Herring River provides a unique opportunity to test this hypothesis.

Restoration of the Herring River will involve a number of government and private entities, including the Town of Wellfleet, which holds the title to the dike, the state Department of Environmental Protection, which has control of the valves within the structure and has regulatory authority over adjacent wetlands, the Chequesset Yacht and Country Club, a local golf course expected to be affected by increased water levels after restoration, two private homeowners also within the floodplain and CACO.

<u>Hatches Harbor</u>.

Prior to 1930, Hatches Harbor was a productive 200-acre salt marsh and open water embayment. Since then, at least 100 hectares of the Hatches Harbor coastal floodplain and salt marsh system have been isolated from tidal exchange by a dike. Originally constructed to drain the landward half of the wetland for mosquito control, the structure's sole present purpose is to provide flood protection for a municipal airport. National Park Service research has shown, however, that the complete diking of tidal flow is not necessary in order to protect the airport from occasional storm tides. Bathymetric surveys, tide height studies and modeling have indicated that a substantial area of the original marsh can be restored by reintroducing tidal flow through enlarged culverts in the dike structure, with no impact to the airport.

A conceptual restoration and monitoring plan was accepted by all ten local, state and federal agencies with interests in either airport operations or local land management, including wetland protection, and the construction of new culverts to allow increased tidal flow was completed in 1999. The culverts are now being opened incrementally, and preliminary data has indicated that the increased tidal flow is positively affecting estuarine fish use and native salt marsh vegetation.

<u>Pamet River</u>.

Pamet Harbor, located on Cape Cod Bay, was once a viable commercial port that served a large fleet of local fishing vessels operating in the cod and mackerel industry (Giese et al., 1993 and 1985). During the mid-1800s, commercial fishing fleets competed for space to anchor in the harbor and residents began to alter the hydrology of the Pamet in

Estuarine Habitat Restoration, continued.

hopes of increasing the harbor's capabilities (Giese et al., 1985). From 1850 to 1930, much of the estuary was diked and dredged. Wilder's Dike was built in 1869 to replace a rotting bridge across the mid-section of the Great Pamet River and in 1950, a clapper valve and dike structure were built to accommodate the construction of Route 6 (Giese et al., 1993).

The diking of the Pamet established two distinct hydrological reaches, the Upper Pamet and the Lower Pamet. East of the tide gate located just west of Route 6, the Upper Pamet is freshwater with a watershed encompassing approximately 192 acres. Many upland species of salt-intolerant plants have invaded the area. Precipitation and groundwater discharge from the Pamet and Chequesset lenses are continually recharging this section of the Pamet, which flows slowly west into the Lower Pamet, a salt marsh estuary (National Park Service, 1986).

The Lower Pamet is an intertidal estuary, greatly stressed by past alterations that have reduced natural tidal circulation and in turn increased shoaling and sedimentation (Giese et al., 1993). Tidal channel beds, except for the outermost section of the inlet channel, are higher than mean low tide in Cape Cod Bay. Restoring tidal flow to the Pamet River is expected to increase natural flushing in the estuary, which would in turn improve water quality, maintain habitat diversity and balance sediment loads in the Pamet River Valley. Additionally, restoration of natural flows would allow the salt marsh to regain a state of equilibrium between sea level and wetland elevations in the Upper Pamet.

<u>Pilgrim Lake</u>.

Pilgrim Lake is a 291-hectare coastal lagoon that functioned as a tidal back barrier estuary and salt marsh before it was isolated from Cape Cod Bay in 1868, purportedly to prevent sand from filling Provincetown Harbor. After this effective diking, the system freshened with current salt levels at about 6.8 parts per thousand (ppt), or 20 percent of seawater levels. Sand from the migrating dunes to the northwest has apparently shoaled the impounded "lake" to an average depth of 1.3 meters, and the waters are hypereutrophic with large blooms of nitrogen-fixing, blue-green bacteria.

In 1956, nuisance mosquito problems prompted the state to install a drainage system consisting of a weir at High Head Road and a culvert carrying water from Pilgrim Lake under Routes 6 and 6A to discharge into Cape Cod Bay. With two flap valves in the culvert to prevent seawater from entering the lake at high tide, the system was intended to lower the level of the lake, thereby reducing the extent of floodwater mosquito breeding sites in surrounding wetlands. Minimum lake level was determined by the height of the weir boards. The complexity of management, and the lack of a scientifically-based management plan, was demonstrated in 1968 when reductions in the lake level for mosquito control resulted in a massive kill of introduced carp and other fish, apparently due to low oxygen and perhaps high salinity. Shortly thereafter, chironomid midges emerged in large numbers, impacting a local tourist trade. Although not an approved activity now, the lake was sprayed with the organophosphate Abate,

Estuarine Habitat Restoration, continued.

potentially killing other beneficial invertebrates as well as midges. Whether the change in lake level, the removal of predatory fish, or changes in lake or sediment chemistry was the cause of the midge problem was never determined; however, this experience discouraged further manipulations of lake level or experiments in restoring seawater flow. Recent review of the midge emergence (J. Portnoy, unpublished report 1991) suggests that the outbreak may have been more directly related to the water drawdown, and not to the release from fish predation pressures.

A fish kill of over 30,000 juvenile alewives and hundreds of white perch in September 2001, likely due to oxygen depletion resulting from the lack of tidal exchange in the Pilgrim Lake system, prompted an experimental opening of the tide gates beginning in December 2001. Tide height and salinity monitoring was conducted prior to the opening of the gates and will continue with the gates open; if salinity remains below 10 ppt over most of the "lake," the gates will remain open indefinitely. A detailed hydrodynamic assessment of the Pilgrim Lake system is still critically needed, however, in order to develop a more comprehensive program for possible estuarine restoration.

Research Needs.

<u>Herring River.</u>

Monitor Herring River Dissolved Oxygen: In order to mitigate further die-offs, a fish gate was constructed in 1986 at the outlet of the Herring Pond in Wellfleet. The gate is used in the summer to block downstream passage of juvenile fish until adequate oxygen levels return to the river. Dissolved oxygen levels are monitored three time a week in the summer at a permanent sampling station within the Herring River. When anoxic conditions are identified (dissolved oxygen of 3 ppm or less), the fish gate is closed. Once dissolved oxygen in the river has returned to above lethal levels, the gate is re-opened. Continued seasonal monitoring is required in order to both ensure the health of CACO's native anadromous fish populations and to track long-term changes in the water quality of the Herring River.

Monitor Ecological Changes Resulting from Restoration: CACO and cooperators have established a detailed description of this estuary's biological, physical and chemical environment over the past ten years of research. As tidal flow is returned, tide heights, water quality, wetland vegetation, benthic invertebrate populations, salt-fresh groundwater relationships, mosquito populations and aquatic fauna need to be regularly monitored for change. Given the adjustability of the dike structure, such ecological changes will likely require measurement in small increments. This strategy will also provide an opportunity for an experimental analysis of the hydrological and geochemical effects of sea level rise, as projected with global warming.

Estuarine Habitat Restoration, continued.

Hatches Harbor.

Cape Cod National Seashore staff have been amassing physical, biological and water quality data on the Hatches Harbor system since 1987 in preparation for what has been described as "the largest single wetland restoration project in the history of Massachusetts" (Portnoy, 1990). In 1999, CACO began incrementally opening the new enlarged culverts, and post-restoration monitoring for changes in hydrology and wetland vegetation was initiated. Continued long-term monitoring of ecological changes following restoration is now needed.

Pamet River.

Historic monitoring of the Pamet River includes elevation surveys and some salinity studies after the barrier beach overwashed in 1991 and 1992. The overwashes made it clear that although this system is diked, it still functions as a back-barrier wetland. Retention of seawater between the overwashed dune and the dike highlighted the inadequate size of present culverts for water discharge. Proposals to restore the Pamet River prompted a recently completed U.S. Army Corps of Engineers study (Kedzierski et al., 1998) of culvert alternatives, which predicts the hydrological, ecological and social effects of tidal restoration. Nevertheless, monitoring is still necessary to assess the system's current functions and values as freshwater wetland habitat and to further evaluate the need for tidal restoration. Especially important is the question of *Phragmites* spread on the floodplain. This invasive grass is well-established in the Pamet River floodplain and could form a monoculture, particularly if present freshwater vegetation is stressed by occasional overwashes of seawater. Monitoring should concentrate on topography, vegetation, soil conditions, hydrology and surface water chemistry.

Pilgrim Lake and Salt Meadow.

An intensive investigation of the physical processes attendant to returning tidal flow to Pilgrim Lake and Salt Meadow is needed, and should include:

1. a description of the system's current tidal and salinity regime, including an assessment of control structures (i.e. culverts, clapper valves and the weir) relative to lake hydrology, hydrography and salinity;
2. topographic and sediment mapping -- detailed topographic data should be collected for the entire floodplain and barrier beach system. Manmade structures (i.e. culverts, weirs and roadways) within the floodplain should also be surveyed, and sediments should be sampled throughout the lake and ditch drainage system for grain size, organic content and resistance to erosion;
3. numerical modeling of the present hydrodynamics and sedimentation; and
4. recommendations for potential tidal restoration scenarios, including modeling and assessment of their physical effects (tide heights, salinity distributions and sedimentation).

Estuarine Habitat Restoration, continued.

(See "Coastal Bays and Estuaries" for related project descriptions.)

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Groundwater Withdrawal.

Background.

The surface freshwater and estuarine resources of Cape Cod National Seashore are dependent upon several thin lenses of fresh groundwater floating atop a base of saltwater beneath the Cape peninsula. The thickness of each freshwater lens varies according to its soil composition (e.g. grain size), depth to bedrock, rate of recharge from precipitation and the width of the Cape at each point in the lens. Hydrogeologically separated from one another by tidal rivers that cut across the Cape, the Pilgrim, Pamet, Chequesset and Nauset lenses are vital to sustaining the outer Cape's cultural and ecological resources. They are the outer Cape's sole source of potable water, and the only hydrologic resource for freshwater dependent flora and fauna.

The only source of freshwater to the lenses in the outer Cape aquifer is precipitation (40"- 47" per year). Just under half of the yearly rainfall (18"- 22" per year) infiltrates the aquifer and recharges the groundwater system. Precipitation that is not recharged to the aquifer evaporates or is transpired by plants. (Surface runoff is negligible because of the highly permeable soils of the Outer Cape.) A great percentage of the recharge passes slowly through the aquifer and is discharged into the surrounding ocean; every day, millions of gallons of fresh groundwater seep out of the ground directly into estuaries and eventually into the ocean, where they help to regulate water chemistry (Cape Cod Planning and Economic Development Commission 1978)

Under natural hydrologic conditions, the freshwater and saltwater flow systems are assumed to be in hydrodynamic equilibrium: groundwater discharge from the freshwater aquifer is balanced by recharge from precipitation, resulting in a static interface between the two flow systems. Decreases in aquifer recharge or increases in groundwater pumping may however decrease the rate of coastal freshwater discharge, creating a landward movement of the boundary of the freshwater lens.

Significant growth in the number of summer and permanent residents on Cape Cod has dramatically increased groundwater use during the past thirty years, placing stress on groundwater resources (Persky, 1986). Substantial local withdrawals of groundwater, e.g. municipal well fields, result in lateral zones of depression on the water table, with the greatest effect occurring upgradient of the withdrawal site. Any wetlands within this affected zone thus experience an artificially lowered water table. Because of the relative densities of fresh and salt water, the depth of the fresh lens at any location is about forty times its height above mean sea level. This relation dictates, for example, that an artificial depression of the water table created by pumping merely two feet will result in an 80-foot upconing of salty seawater into the naturally fresh groundwater lens. Such chronic lowering of surface waters in emergent wetlands may produce major shifts in floral dominance and can also limit flooded habitat for dependent aquatic fauna. In addition, the effects of prolonged pumping have been shown to be cumulative.

Groundwater Withdrawal, continued.

With increasing permanent and seasonal populations comes a need to expand public water supply capabilities and indeed some areas not currently being served by public water supply systems will need to develop systems in the future as a result of water quality concerns. Research on the extent and impact of long-term declines in groundwater, pond and wetland levels, in the quantity of streamflow and in the possibility of saltwater intrusion from the surrounding ocean is critical for water resource management decisions, both now and in the future.

Research Needs.

Research is currently being conducted by the United States Geological Survey-Biological Resources Division, National Park Service, Cape Cod Commission and Massachusetts Audubon Society on the potential hydrological, biogeochemical and ecological effects of municipal groundwater withdrawals at vernal ponds, kettle ponds and littoral zones. The hydrologic environment has been described and modeled, and several rounds of vegetation, aquatic invertebrate and chemical sampling have been completed. Expansion of the current sampling areas to include the Atlantic white cedar swamp and interdunal ponds, and long-term monitoring of all sampling sites is needed for an accurate evaluation of groundwater withdrawal impacts on surface groundwater systems.

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The Gull Pond Sluiceway.

Background.

During the 1800s, Wellfleet residents dug and stabilized an artificial sluiceway between Gull and Higgins ponds in order to provide herring with additional spawning waters in Gull Pond, thereby expanding the existing Herring River anadromous fish run. The National Park Service has been maintaining the sluiceway with periodic dredging since the establishment of Cape Cod National Seashore in 1961 and has recently allowed this practice to be taken over by local volunteers working under the direction of the Massachusetts Herring Run Protection Program. Traditionally, NPS has maintained the sluiceway for fish passage, and because little is known about the effects on Gull Pond of allowing the sluiceway to fill in. While the sluiceway remains a part of the cultural landscape of Cape Cod, a National Seashore management objective requiring CACO management to "allow natural processes to continue unimpeded in natural zones . . . and neutralize the effects of human intervention where it has adversely affected natural systems" clearly contradicts the current sluiceway preservation efforts. Whether or not to continue maintaining the historical sluiceway between Gull and Higgins ponds is a complex question with potential impacts on the natural biota of the ponds, the introduced trout fishery in Gull Pond, the anadromous herring run in the Herring River, and Gull Pond water quality.

Without the flow of surface water provided by the sluiceway, mature alewives (*Alosa pseudoharengus*) and blue-backed herring (*Alosa aestivalis*) would no longer be able to enter Gull Pond to spawn in the spring and juveniles of the species would be unable to leave the pond for their migration to the sea in the summer and fall. The present influx of these fish into Gull Pond may have a considerable impact upon its food chains and nutrient cycles. Adult fish remain at their spawning grounds anywhere from a few days to many weeks and, while there, mortality may reach as high as 57 percent (Durbin et al., 1979). Additionally, young alewives spend part or all of their first summer in the nursery area before migrating seaward. Since most of their growth and nutrient uptake occurs at sea, these fish may represent a significant nutrient source to their freshwater spawning and nursery grounds (through shedding of eggs and sperm, excretions and the carcasses of dead spawners). Such nutrient additions may be particularly pronounced in slow-flushing, groundwater-fed ponds like Gull Pond, which has a residence time of 10-15 years (Mitchell and Soukup, 1981).

Alewives can also considerably alter an existing aquatic community of plants and animals through their role in the food chain. Alewives are planktivores, fish that eat zooplankton. Zooplankton are herbivores that feed on algae in lakes and ponds and, in turn, reduce the amount of algae present there. When planktivores such as the alewife are introduced to a pond, zooplankton decrease and algae increase with the reduced grazing pressure (Shapiro, 1990). Based on this occurrence, which has been observed in several locations including Lake Michigan (Shapiro, 1990), Gull Pond would hypothetically see a decrease in algal growth after the sluiceway is closed and herring are prevented from entering.

The Gull Pond Sluiceway, continued.

Current levels of algal density may be a factor in the relatively low clarity observed in Gull Pond. Reduced clarity may, in turn, contribute to the dissolved oxygen deficit observed at the bottom of the pond by reducing the level of light penetration at this depth and increasing the deposition of organic matter to the bottom. This change may eventually affect, among other things, the trout fishery managed by the Massachusetts Division of Fisheries and Wildlife in the pond (Mitchell and Soukup, 1981).

Research Needs.

History and ecology are highly interconnected on the issue of maintaining the sluiceway to Gull Pond. From a historical perspective, the nearly 200-year existence of the sluiceway (Winkler, 1994) is a strong argument that it should be maintained, just as other historic structures are maintained in the park. From an ecological perspective, the sluiceway is neither natural nor self-maintaining, as natural processes would cause it to fill in. Determining whether or not it creates an overall ecological benefit to the entire Herring River ecosystem is critical to deciding whether or not to continue sluiceway maintenance. As outlined in CACO's Water Resources Management Plan (Godfrey et al., 1999), a detailed nutrient budget for Gull Pond and the freshwater reach of the Herring System (see the related project under "Kettle Ponds") and research into the trophic structure of Gull Pond and the chain of ponds, river and estuary downstream are needed in order to understand the full ecological impact of the sluiceway. Most of the research effort should focus on Gull Pond itself, under the assumption that the anadromous fishery in downstream lakes and flowing systems would not change significantly if the sluiceway was allowed to fill in. However, sufficient data should be collected to verify that assumption. Standard procedures for determining a nutrient budget by measuring all inputs and outputs should be followed. Measurements of watershed inputs and outputs will necessarily focus on groundwater flow and outlet loss, and anadromous fish should be counted as a net input, necessitating counts and average size estimates for incoming and outgoing fish. Trophic structure analysis will require collection, identification and counting of phytoplankton and zooplankton at least once a month.

Additionally, if the nutrient contribution of the anadromous run is found to be large and if the trophic structure does appear to be skewed in ways typical of herring grazing on zooplankton, a study modeling the effect of removing the herring run from Gull Pond will need to be completed. Model development should reflect the steady-state endpoints of both changes in biomass and qualitative characteristics (gross species composition), as both are key to determining ecological benefit.

When a management decision is made to either maintain the sluiceway or to let it close naturally, a monitoring program should be initiated with sufficient detail to reveal changes prior to ecological effects becoming irreversible.

The Gull Pond Sluiceway, continued.

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Inter-Dune Wetlands.

Background.

The parabolic dunefields of North Truro and Provincetown contain numerous depressions, some of which reach down to the water table to form shallow wetlands that serve as "oases" within the larger dune complexes. Though quite variable in extent and composition, these dune slack ponds and wetlands support a distinct and highly diverse plant community and provide vital sources of freshwater and forage for wildlife. The interdunal bogs have been field surveyed for the presence of state-listed plants, and are described as being unusual because of their species diversity and community type (LeBlond, 1990). Preliminary surveys also suggest that these wetlands are an important breeding habitat for the Eastern spadefoot toad (*Scaphiopus holbrookii*), a Massachusetts state threatened species, and that the Province Lands in general support what may be the largest concentration of this species in the state. These interdunal wetlands may additionally serve as seed sources for vegetation throughout the Province Lands, and as such are particularly vital to the natural revegetation of dunes via primary succession. These relatively small and scattered ecosystems thus provide crucial ecological services for overall landscape processes as well as endangered species within Cape Cod National Seashore.

Intensive development in Provincetown has put increasing demands on groundwater resources in the Province Lands area. As municipal wells and wastewater treatment facilities are installed adjacent to CACO boundaries, serious concerns are arising over the potential effect these water table modifications may have on dune slack wetlands. Additionally, re-routing of administrative and private landowner access roads has conflicted with the preservation of these sensitive wetlands in recent years. A major portion of the Province Lands has been designated a historic district on the National Register of Historic Places, and the relocation of dune shacks within that district may also be a future management issue. Our ability to protect these wetlands and the species that rely on them is at present severely hampered by a lack of baseline data on their spatial distribution and water quality.

Research Needs.

Map Bog Locations: The dune wetlands within Cape Cod National Seashore are not always detectable on USGS maps and have not yet been mapped by other means. These areas need to be mapped for incorporation into CACO's Geographic Information System, and existing data on state listed rare plants incorporated into a relational database for use in determining road and residence relocation, revegetation sites, etc.

Inter-Dune Wetlands, continued.

Monitor Water Quality: Monitoring of dune bog water quality, both immediately and on a long-term basis and in conjunction with the past paleo-limnological study of the Provincetown area water bodies (Winkler, 1990), is critically needed.

Develop and Implement Monitoring Program: Development and implementation of an inventory and monitoring plan for these wetlands, analogous to the plans for CACO's estuarine resources and kettle ponds, is needed in order to document the current composition of their flora and fauna and to track future changes in CACO's interdunal plant and animal communities.

Evaluate Groundwater Drawdown Impacts: Given the obvious dependence of Province Lands flora and fauna on dune slack wetlands and the permanence of municipal wells and wastewater facilities, the potential for making a lasting and irreversible impact to the Province Lands systems is severe without basic data on their expected response to these groundwater modifications. Once baseline inventories of the biotic and abiotic components of CACO's dune slacks have been completed, investigations into the impacts of groundwater drawdown on inter-dune wetland hydrology, and the associated effects on plants and wildlife, are critically needed.

(See related project descriptions under "Groundwater Withdrawal.")

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Invasive Aquatic Species.

Background.

Given the proximity of Cape Cod National Seashore to the major shipping ports of Boston and New York and the major role that ballast waters have played in the introduction of non-native species to North America, it may not be surprising that a number of invasive aquatic species have taken hold in Cape waters. The European green crab (*Carcinus maenas*), a widely-distributed invasive that feeds voraciously on both bivalves and the larvae of other crab species, has the potential to restructure the outer Cape's crab population and to devastate near-shore crustacean and invertebrate nurseries. The Japanese shore crab (*Hemigrapsus sanguineus*) may also crowd out native marine species and pose a threat to local shellfisheries, and common carp (*Cyprinus carpio*), an Asian freshwater species, has contributed heavily to the anoxic conditions of Pilgrim Lake in Truro. Green fleece (*Codium fragile*), an invasive marine algae, is adversely affecting shellfish populations throughout the seashore and Japanese knotweed (*Polygonum cuspidatum*), a quick-spreading introduced wetland weed resistant to eradication, occurs just outside CACO boundaries in Provincetown. Water hyacinth (*Eichhornia crassipes*), purple loosestrife (*Lycopodium sabinifolium*) and common reed (*Phragmites australis*) have all gained a foothold in CACO's wetlands, and numerous other introduced aquatic and wetland species may also be displacing native species and altering wetland communities throughout the park. The widespread potential for a severe impact to native marine and freshwater systems on the outer Cape creates a critical need for the documentation of invasive aquatic species occurrence and density at CACO, to be followed by control efforts and long-term monitoring.

Research Needs.

A baseline inventory of CACO's non-native plant species, including invasive wetland flora, was completed in 2001; a similar study is still needed for invasive aquatic fauna. Long-term monitoring and a CACO-specific invasive species management plan are also needed to mitigate the impact of introduced aquatic plants and animals on native species within the park.

Kettle Ponds.

Background.

The twenty kettle ponds within Cape Cod National Seashore are a unique and sensitive

resource with significant ecological, aesthetic and recreational value. Formed by ice blocks left behind during the last glacial retreat and filled with freshwater as a result of precipitation and sea level rise, these kettle ponds are surface exposures of Cape Cod's water table. They are also home to an unusual assemblage of plants and animals. Kettle ponds support myriad and diverse aquatic fauna from leeches to dragonflies, including many state listed rare species, and the kettle pond environment is the preeminent rare plant habitat in the park. In 1990, LeBlond identified eight state listed plant species at eighteen sites within CACO kettle pond habitats. Largely oligo- or mesotrophic and naturally acidic (Soukup, 1977), the ponds are extremely clear and biologically unproductive, and are highly susceptible to changes in water quality caused by increased sedimentation and nutrient loading.

After the ocean and bay beaches, the freshwater kettle ponds are likely the most visited natural area within the seashore. Fishing, boating, swimming and picnicking are popular activities at many of the ponds. In addition, there are year-round and seasonal houses on some of the pond shorelines. All of these adjacent dwellings rely on septic systems, which, given the porous nature of the groundwater aquifer, may contribute to pond eutrophication. Increasing numbers of seasonal cottages are being converted to year-round residences, with a resulting year-round impact, not only from septic effluent, but also from gardening herbicides, fertilizers and eroded soils. Land ownership of the ponds and adjacent shorelines varies between the National Park Service, the state of Massachusetts, individual towns and private citizens. Given the intensity of the recreation in, on and around the ponds, the varying ownership patterns and multiple jurisdictions surrounding them and their inherent biological fragility, managing kettle ponds to protect water quality and adjacent freshwater habitats has become one of the most complicated and important management programs at CACO.

With concerns for apparent eutrophication caused by human-induced nutrient loading, an intensive annual water quality monitoring program has been ongoing at CACO's kettle ponds for the last nine years. Bi-weekly measurements profiling pH, temperature, conductivity, water transparency and dissolved oxygen are now determined during the summer months at fifteen of the twenty kettle ponds within CACO. In addition, chlorophyll α and nutrients are monitored semi-annually (April and August), and pH and alkalinity have been determined quarterly at nearly all park freshwater bodies since 1984. This monitoring program has become institutionalized at CACO and is being conducted by seasonal resource management biological technicians.

Kettle Ponds, continued.

Research Needs.

Review and Evaluate Existing Water Quality Data: Water issues on the outer Cape, and kettle ponds in particular, have been the focus of considerable high quality research in recent years. Despite this extensive research effort, a consistent, quality-defined synthesis describing past and present pond conditions, trends, and projections for the future is still needed for a complete understanding of the issues surrounding kettle pond management at CACO. This work is expected to build upon that of the Kettle Pond Data Atlas (Portnoy et al., 2001) and should include recommendations for future study.

Evaluate Feasibility of Remote Multi-Parameter Data Logging: Remote sensing of aquatic environments has become a reality for many types of key water quality data, lessening the need for staff to frequently monitor a number of easily measured parameters. Coupling such multi-probe devices with cellular phone uplinks can also provide real-time information, which can be used to alert resource managers to unusual events in the ecosystem and to increase public awareness of pond conditions. A review of available multi-parameter probes, logging and real-time systems, including prioritized CACO data needs and information dissemination possibilities and a cost-effectiveness evaluation, is needed in order to evaluate the feasibility of implementing this new technology at CACO.

Monitor Pond Phytoplankton: Specific phytoplankton associations can be used as indicators of a pond's acidity and nutrient levels, and may provide early warnings of changing environmental conditions. Due to their short generation times and quick, detectable responses to environmental change, pond algae populations can express environmental fluctuations in just a season or two, where other means of observation might allow the same changes to remain unnoticed for years. Regular monitoring of phytoplankton species composition and abundance in CACO kettle ponds would thus be a valuable supplement to CACO's well-established water quality monitoring program.

Monitor Kettle Pond Margin and Wetland Transition Macrophytes: Given the inherently low nutrient levels at these ponds, impacts from septic effluents on pond water quality and associated flora and fauna are of real concern. A baseline survey of pond margin and wetland transition macrophytes, including maps of current macrophyte distribution along pond shorelines and inventories of the species composition and abundance of emergent vegetation at each pond, has recently been completed (Roman et al., 2001). Long-term monitoring is now necessary to assess and detect changes over time in pond margin species composition and distribution. Established transects should be revisited every 5-10 years in order to monitor such vegetation change relative to water chemistry, adjacent land use, atmospheric deposition and climate change.

Kettle Ponds, continued.

Inventory Aquatic Macrophytes: In addition to increasing pond margin and wetland transition macrophytes, increased nutrient loading from septic systems and other sources can also greatly increase aquatic macrophyte production. While good historical information exists on the presence of pond shoreline plants (Soukup, 1977; Hinds and Hathaway, 1968), there is limited quantitative data on the abundance of these species. So far, baseline inventories have only been completed for five of the twenty ponds. The remaining fifteen ponds need to be inventoried for existing emergent vegetation according to techniques currently used by the Massachusetts Department of Environmental Protection and by the Massachusetts Water Watch Partnership, and adapted from the United States Environmental Protection Agency. Once these baseline surveys have been completed, a long-term monitoring program must be designed and implemented in order to detect and evaluate any changes in plant species abundance and composition.

Evaluate the Role of Aquatic Macrophytes in Nutrient Sequestering: New research suggests that the aquatic macrophytes which occupy the shorelines and shallow waters of CACO kettle ponds may be vital to maintaining pond clarity. Like the growth of algae, the growth of aquatic macrophytes in Cape kettle ponds is largely dependent on the supply of phosphorous, an element that is scarce in native Cape soils but one that is introduced in significant quantities by human development and recreational activities. In deep kettle ponds where rooted plants are limited to the shorelines, excess phosphorous mostly benefits planktonic algae, which cloud the water and strip it of oxygen during their decomposition process, creating the potential for massive fish kills. Not only do aquatic plants compete with these algae for phosphorous in the water column, but new research suggests that they may also reduce eutrophication by producing conditions in pond sediments that lead to permanent phosphorous sequestration. In the presence of oxygen brought by these plants into their root zones, soluble ferrous iron is oxidized to form nonsoluble ferric oxyhydroxide, which absorbs phosphate. The phosphorous is thereby removed from the groundwater before it reaches the open pond environment. In the same way, phosphorous that leaks from decomposing organic matter along the pond's shorelines may be "captured" in the plant's aerated root zones and kept out of pond water, to the detriment of algae and benefit of pond clarity and overall pond health. Preliminary analysis of sediments in vegetated versus non-vegetated areas indicates that phosphorus is more abundant in the sediments of vegetated areas (Portnoy, unpublished data, 1997). However, many questions still remain: Do the macrophytes scavenge phosphorous from the water column and sequester it in the aerobic zone? Do they provide the chemical environment necessary for converting phosphorous pollutants in groundwater to a nonsoluble form before they can become part of the plant or algal biomass? Is the phosphorous permanently sequestered or only temporarily sequestered for later release? Further evaluation of the phosphorous sequestration process is necessary, and will require analysis of the phosphorous partitions and redox potential in the sediments of both vegetated and non-vegetated areas. Samples should be collected over several seasons to determine the permanence of the sequestration effect.

Kettle Ponds, continued.

Develop Nutrient Budgets and a Nutrient Loading Risk Assessment for Each Pond: Understanding the causes of kettle pond eutrophication involves understanding the dynamics of nutrient supply, pond response and loss of pond nutrients. Partitioning the sources of nutrient input into ponds, particularly during critical periods of biological activity, is thus necessary in order for resource managers to make informed decisions about water quality maintenance and restoration. Such nutrient budgets need to be developed for all twenty kettle ponds within the seashore, according to the priority order established by Martin et al. in 1993. Since the nutrient inputs and outputs at CACO kettle ponds are primarily groundwater with potentially significant inputs from the atmosphere (including temporary avian visitors), the task of developing such nutrient budgets at CACO requires a close coupling of hydrogeological and limnological techniques. Although well-developed nutrient loading models exist for surface water input and output systems, no models are currently in place for groundwater-dominated systems and so initial research will require direct measurement of pond inputs. Such measurement will require a shoreline ring of multi-level piezometers to intercept groundwater from the watershed (The same well network is required for the study of septic system impacts currently being initiated by the USGS –see below—, and thus may be coupled with the USGS research.) The National Atmospheric Deposition Program site may be used for additional nutrient measurements, and work done by Portnoy on avian contributions (1990) along with waterfowl counts may be used to estimate transient contributions. Inlets and outlets should be sampled with grab sample methods at monthly intervals and after significant precipitation events, and in-lake monitoring should follow the protocols described in Martin et al. (1993). As the database develops, correlational models between land use and hydrogeological characteristics should be developed with the hope that later nutrient budgets can be related to these models rather than to the more costly direct measurement techniques. Upon completion of these nutrient budgets and of the septic system leachate research described below, the impact of individual septic systems should be determined, and an estimation of aquifer water quality based on area-wide sources of pollution should be developed. A sensitivity analysis should also be conducted to determine the impact of potential changes in CACO practices on aquifer and kettle pond water quality.

Monitor Septic Leachates: Nutrient loading from failing septic systems or cesspools of adjacent pondshore cottages and homes is, as mentioned above, a major management concern. At present, potential impacts from these systems are not linked to their sources. An investigation of nutrient transport along shoreline flow paths from septic leach fields is underway at Gull Pond (Coleman et al., 2000). However, a long-term monitoring program for all ponds is still needed in order for CACO staff to define point sources of septic effluent and evaluate the effectiveness of future modifications or upgrading of private and NPS septic disposal systems. Additionally, the rate of nitrate and phosphorous attenuation relative to the distance of septic systems from pond shorelines needs to be determined. Replicate residences should be selected for both year-round and seasonal impacts, and with septic systems far enough from a pond to permit accurate evaluation. Sampling of shallow wells with 1 to 5-foot screened intervals

Kettle Ponds, continued.

should be conducted monthly for one year to evaluate seasonal affects on the rate of nutrient attenuation.

Characterize Pond Hydrogeology: Hydrologic characterization of Gull and Duck ponds (Horsley & Witten, 1996, Sobczak et al., in review) has done much to explain their very different water chemistries. Indeed, as surrounding land use changes, the influence of local hydrology on all the kettle ponds is becoming even more important. CACO has installed siphon wells at nine ponds as part of the Seashore's Inventory and Monitoring Program (McCobb et al., 1999), but local bench marks and staff gauges are still needed at the remaining eleven. Additionally, the USGS has initiated research on an integrated groundwater model for the entire outer Cape (Masterson and Barlow, 2000). This study will delineate groundwater flow paths so that contributing areas can be mapped upgradient of each pond basin. Once available, this information should be combined with land use data and coupled to empirical and geochemical modeling results of the nutrient transport study (Colman et al., 2000) to estimate the influx of nutrients and other solutes to each pond via groundwater flow.

Research Post-Glacial Pond Development: Investigations into the paleoecology of CACO kettle ponds have been initiated as an effort to understand how modern environmental problems such as acid rain, toxic atmospheric deposition, cultural eutrophication and pollution of ground and surface waters have degraded these freshwater systems. To know how CACO ponds have responded to local and regional environmental impacts, it is necessary to compare recent changes in the ponds with past (that is, pre-European settlement) changes. In the absence of historical records, only paleoecological study of lake sediment cores can provide this long-term perspective. Several paleoecology studies have been already been completed at CACO (Winkler 1982, 1985, 1988, 1989, 1994 and 1996, and Winkler and Sanford, 1995), and complete sediment cores have been taken at ten of the twenty kettle ponds. Research is still required, however, to determine the origin and basal ages of the remaining ponds. In addition to its role in defining the post-glacial landscape and time frame within which the kettle ponds developed, such research is expected to help explain the interruption of pond sediments by massive sand and gravel deposition in the early- to mid-Holocene era, and also to increase the overall understanding of topography on the outer Cape since deglaciation, the building of barrier beaches, bays and salt marshes, and the effects of these physiographic changes on the development of the kettle ponds and on the changes in the flow of water across the narrow outer Cape peninsula.

Research Changing Diatom Assemblages: Specific diatom assemblages can be used as indicators of a number of a pond's contemporary water quality parameters (pH, salinity, water level, etc.), and diatoms found in pond sediment can reveal the same characteristics about a pond's past. The species composition of these water-quality-sensitive assemblages has changed, however, since the time of European settlement. Diatoms indicating acid conditions before settlement are different from those that indicate acid conditions now and, similarly, diatoms indicating nutrient increases today are different from those species that indicated similar trophic changes in the past.

Kettle Ponds, continued.

Further study of this species replacement is required in order to fully understand the circumstances surrounding these relatively recent biological changes in CACO kettle ponds.

Survey Invasive Species and Develop an Emergency Response Plan: Throughout Massachusetts, severe lake and pond problems are resulting from the introduction of invasive, introduced species of aquatic macrophytes. While many of the invasive species common to Massachusetts wetlands prefer nutrient-rich, relatively hard water and higher pH than what is typically found at CACO kettle ponds, others are broadly tolerant. Within a few years, an accidental introduction can spread throughout an entire pond, severely impacting both water quality and native plant and animal species. In order to detect the presence of these potentially harmful plants before serious damage occurs, a yearly qualitative survey for initial colonization of any species identified by Mattson et al. (1997) as serious potential threats to Massachusetts lakes and ponds is necessary. An emergency response plan should also be developed for use in the event that an invasion is detected, as eradication is far easier initially than in later years when whole pond chemical treatment, a technique inconsistent with National Seashore policy because of its effects on native species as well as the targeted invasives, may be the only alternative.

Inventory Benthic Invertebrates: No information currently exists on kettle pond benthic invertebrates in Cape Cod National Seashore. A complete baseline survey of benthic invertebrates in each pond, followed by the design and implementation of a long-term monitoring program, is necessary in order to evaluate the effects of the state's active fishery enhancement program (stocking and pond liming). In addition, metals concentrations in invertebrates are useful indicators of water quality changes, especially acid balance (which is of particular concern given the well-documented history of acid deposition on Cape Cod.) Baseline data on benthic invertebrates is thus also critically needed in order to understand the impacts of water quality changes on the outer Cape. Initial investigations should focus on ponds selected to represent a full range of water chemistries, depths, sediment types and plant communities, and eventually expand to include all twenty kettle ponds within CACO boundaries. Functional models of faunal/habitat relationships need to be developed and verified, and detailed protocols for characterizing benthic invertebrate abundance and diversity, along with important environmental attributes, should also be produced.

Research the Zooplankton Community in Duck Pond: Summer zooplankton hauls at Duck Pond, a 5.1-hectare, 18-meter-deep kettle located at the top of the Chequesset groundwater lens in South Wellfleet, typically yield only one or two copepod species (MacCoy 1958), yet the sediment record shows that *Neobosmina tubicen, Diaphanosoma* sp. and at least fifteen littoral cladocera species exist in the pond. Research is needed to explain this apparent discrepancy.

Kettle Ponds, continued.

Investigate the Causes of pH Changes in Ryder Pond: The pH of Ryder Pond, an 8.3-hectare, 11-meter-deep kettle pond located in the Wellfleet outwash plain, declined dramatically from 5.8 to 4.3 between 1983 and 1992, increased slowly to 4.6 by 1999, and then rapidly recovered to pH 5.4 by April 2000. None of the many adjacent ponds of similar morphometry and geologic setting exhibited a similar change in pH and, more regionally, the median pH of ponds across Massachusetts increased steadily over that same period (Godfrey et al., 1996). Local hydrology, as well as biogeochemistry, may play a major role in these observed water quality changes, and may explain why Ryder behaves so differently than nearby, otherwise similar kettle ponds. Pond water sulfate, monitored since 1985, seems to vary directly with acidity, increasing from an original 7 mg/L to a maximum of 14 mg/L by 1993, and declining along with acidity thereafter. Ryder Pond also experienced a significant and systematic decrease in mean summer transparency (the result of increased algae production) beginning in 1993. High sulfate has been associated with increased lake production through competition between sulfide and phosphate for iron precipitation or sorption sites (Caraco et al. 1989, 1990). Atmospheric deposition, measured at the local NADP site, is too small, however, to explain the increase in pond water sulfate even if the anion had accumulated conservatively. Pond water chloride varied little (30-33 mg/L) over this period so that sea salt inputs, whether transported as salt spray or in precipitation, were also not an important factor. Thus, the sulfate responsible for the acidification of Ryder Pond must have been mobilized from within the watershed. Research is required to understand the sulfur cycling and sulfate mobilization responsible for such profound changes in the acid balance of Ryder Pond over the past 15 years. The cycling of other elements, especially phosphorus and iron, should also be investigated as likely participants in observed changes in water chemistry and productivity since 1984.

Develop Individual Management Plans for Each Pond: Each of the twenty kettle ponds within CACO has different physical and ecological characteristics, public recreation uses and land ownership patterns. In order to meet the specific needs of these diverse resources, efforts are underway to develop management plans for each of these ponds. These plans will establish the purpose and needs, program direction, responsibilities and scheduled activities necessary to accomplish stated recreation and conservation goals at each pond. Management plans for three kettle ponds completely within NPS jurisdiction (Snow, Round West and Spectacle) have been completed. Development of plans for two other ponds with multiple ownership (Duck and Gull) was started but never finished. Management plans need to be completed for these two ponds, as well as the remaining fifteen. Plans should be developed with the assistance of park staff and, when appropriate, an ad hoc public advisory group.

Develop a Comprehensive Kettle Pond Management Plan: Once individual plans have been completed for at least half of the CACO ponds, work should begin on a comprehensive kettle pond management plan that consolidates common elements from the individual plans while also providing flexibility for their differences. As with the pond-specific plans, the principal goals of the integrated management plan are to

Kettle Ponds, continued.

minimize impact, mitigate problems, preserve sensitive ecosystems, maintain water quality and landscape aesthetics and provide sustainable recreational opportunities for both local landowners and day visitors. Since the solution of many of these issues requires the sustained participation of pond users, they should be incorporated into the planning process at an early stage through public meetings and the use of public advisory groups, as established during the development of the individual pond plans. A technical interagency committee consisting of local, park, state and academic members who are knowledgeable about CACO ponds, the local environment and watershed management should also be established to assist in reviewing existing knowledge about the ponds, recommending a common process for involving the larger community, identifying and prioritizing problems, and evaluating existing and designing new monitoring and management programs.

Inventory Human Impacts: With the high volume of public pond use during the summer, some environmental impact to the adjacent shoreline is inevitable. Unfortunately, relatively little quantitative information presently exists on the condition of pond trails and beaches. These areas, if severely eroded, could be contributing to a deterioration in pond water quality. Most trails have not been catalogued and erosion associated with trail and shoreline use is not known. In addition, some CACO areas appear to be annually enlarging. In many areas, trampling and subsequent loss of ground vegetation, shrubs and tree seedlings continue to be unquantified. A standardized monitoring protocol is currently being developed to provide for the detection and evaluation of human impacts to pond shorelines and adjacent slopes. Upon its completion, long-term monitoring data needs to be collected to provide an objective record of site conditions over time and to allow for an evaluation of impacts. With an active monitoring system in place, pond shore deterioration could be detected and appropriate management actions implemented before severe or irreversible impacts (especially to water quality) occurred. In addition, monitoring use patterns and impacts would provide a mechanism for developing management strategies and for evaluating the success or failure of resource protection measures following their implementation.

Develop Revegetation Plans: Intense and concentrated public use has caused significant bank erosion at a number of kettle ponds. These areas are now devoid of vegetation and sediment from the bank has eroded into the ponds, burying adjacent submerged and emergent vegetation. A recent three-year project resulted in the stabilization and revegetation of some pond shorelines. However, revegetation was only partially successful and many other shorelines require planting and protection. Each impacted area needs to be surveyed, and detailed site maps developed. Using these maps, specific work plans must be generated to re-contour and/or fill eroded slopes, rehabilitate trails, erect fencing and revegetate bare soil. Once revegetation efforts have been completed, follow-up monitoring of the newly established plants will be necessary to evaluate the success or failure of the efforts and to identify any areas that require additional attention.

Kettle Ponds, continued.

Study Public Use: Given the intensity of recreation and potential impacts of CACO visitors, a vital component of any future pond management program must focus on people. Currently, we have no information available about pond users, including how many people visit the ponds, recreational uses of the ponds and pondshores, and public attitudes and expectations about pond management issues. Baseline data about recreation use patterns and people's attitudes are critically needed to provide an objective record of current conditions and to help in directing future management actions aimed at protecting resources. This information would also enable the park to adequately evaluate the success or failure of these actions following their implementation. Specific data needs include:

1. Visitor Use Patterns: an estimation of the numbers of visitors at each pond by specified times of the day and the relative abundance of visitors engaging in various recreational activities;
2. Public Attitudes: Who are pond visitors? What is their knowledge about the sensitivities of the ponds? What are their attitudes about various management alternatives? Why do they visit the ponds and what are they expecting from their visit? What is the quality of their site visit? What are their perceptions of crowding?

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Landfill Impacts on Groundwater.

Background.

Municipal landfills in the towns of Wellfleet, Truro and Provincetown are currently unlined and, with the exception of Provincetown, uncapped solid waste and septage disposal sites within or adjacent to the boundaries of Cape Cod National Seashore. All three introduce leachate high in nitrogen, metals, volatile organic compounds (VOCs) and oxygen demand into the local aquifer, which is the sole source of potable water and the hydrologic source for all freshwater-dependent natural resources on the Outer Cape. These leachate plumes travel with groundwater flow, eventually discharging into surface water resources in and adjacent to CACO. Although actual discharge locations and effects are uncertain, it is likely that the Wellfleet landfill leachate plume flows into the Herring River, that Truro leachate impinges the Pamet River and that the Provincetown plume reaches both nearby ponds and Provincetown Harbor. Potential effects include pond and coastal water eutrophication, oxygen depletion, and metals and VOC toxicity to aquatic biota.

Research Needs.

Evaluate Past Study Design: Prior landfill monitoring efforts in the CACO vicinity need to be studied and evaluated for effectiveness, and a long-term program for improving the monitoring network and techniques needs to be developed. Specific attention should be paid to the scope of previous chemical analyses and to the depths and placement of existing observation wells.

Continue Plume Monitoring: Soil boring has been conducted and monitoring wells established at all three landfills, as well as two in Eastham and Orleans which also have the potential to impact water resources within the seashore, and the contamination plume at each site has been mapped. Additionally, models of the outer Cape groundwater system are currently being developed by the USGS-Water Resources Division (USGS-WRD); when completed, these models should prove useful for tracking plumes throughout the aquifer. Further research at the level of the Provincetown leachate plume study (Urish et al, 1993) is required to define the chemical nature and discharge location(s) of the landfill and septic leachate plumes at the other four sites. Initially, the resolution of water table mapping should be refined to enable more accurate predictions of flow direction and velocity. Electromagnetic soundings should be conducted to suggest leachate depth and flow paths. These data will allow the strategic placement of additional observation wells and soil borings for sampling and monitoring contaminated groundwater quality, both during the study phase and for resource monitoring indefinitely into the future. If, as in the case of Provincetown, leachate is found to enter surface waters, additional impact assessment will need to be conducted with an emphasis on geochemical changes to contaminants and the biological effects of nutrient loading.

In addition to more detailed individual studies for each landfill, a synchronized study of all five sites is necessary to fully evaluate the effects of landfill leachate on outer Cape

Landfill Impacts on Groundwater, continued.

groundwater. In consultation with the Massachusetts Department of Environmental Protection and the USGS – WRD, existing monitoring and observation wells around all five landfills should be revisited, and measurements of specific conductance and pH taken, along with hydrostatic head determinations. Samples should be collected from each well and analyzed for major indicators of contamination, including chloride, alkalinity, sodium, nitrate and dissolved organic carbon. These data should then be entered into CACO's Geographic Information System and contour maps generated to provide a synoptic picture of the landfill plumes impacting the seashore. This synchronized survey should be done annually for three years in order to gauge changes in the plumes.

Literature Review of Capping Methods: Existing landfills in or near CACO clearly need to be capped in order to minimize the creation and migration of toxic leachate into ground and surface waters. A literature review of available landfill closing techniques needs to be undertaken, with particular attention paid to the influence of various methods on the migration of existing contaminant plumes and on further leachate generation. Based on hydrological assumptions about the effects of the capping techniques, numerical modeling of the plumes should be completed and likely scenarios predicted.

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Larvicide Impacts on Native Invertebrates.

Background.

Despite the absence of a public health threat, wetlands on outer Cape Cod have been altered to control dipteran insects for over 300 years. In the nineteenth and twentieth centuries, large areas of the tidal wetlands now included within Cape Cod National Seashore were diked and grid-ditched to reduce breeding habitat for salt marsh populations of nuisance mosquitoes. Since 1938, the state program of nuisance insect management has been conducted by the Cape Cod Mosquito Control Project (CCMCP).

When the seashore was established in the early 1960s, the deeds of conveyance for the Province Lands and Pilgrim State Park included a provision allowing the CCMCP to continue certain activities for the "proper control" of mosquitoes and greenhead flies. Although the CCMCP has no specific authority to conduct nuisance insect control elsewhere in the seashore, ditch maintenance, larvicide treatments and, in the case of Pilgrim Lake, water level control continue throughout CACO wetlands. National Park Service policy normally does not permit native insect control in the absence of a public health emergency. (The regionally important arbovirus eastern equine encephalitis is not a problem on Cape Cod.) The effects of ditch drainage on coastal wetland ecology have been studied (Soukup and Portnoy, 1986; Portnoy, 1999; Roman et al., 1995), and are expected to be mitigated by ongoing salt marsh restoration. Larvicide treatments may have long-term effects on native invertebrates (including mosquitoes) and dependent fauna (Hershey et al., 1998). Researching the impact of mosquito larvicide treatments on native invertebrates will enable both CACO and the CCMCP to make more informed decisions regarding the management of some of CACO's most productive wetland systems.

Research Needs.

Research on the impacts of mosquito larvicide treatments on native invertebrates within Cape Cod National Seashore, as well as an assessment of the efficacy of these treatments on the target organisms, is needed.

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Larvicide Impacts on Native Invertebrates, continued.

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Marine Debris.

Background.

The amount of debris found on beaches and at sea in recent years is a national, indeed global, ecological concern. Debris that is washed ashore not only diminishes the scenic value of beaches, but while adrift at sea it can also be lethal to marine wildlife. Of particular concern is plastic, which accounted for nearly 89 percent of all marine debris found on Cape Cod beaches in a 1990 survey (Manski, 1991). The National Wildlife Federation estimates that over one million birds and 100,000 marine mammals worldwide die each year as a result of ingesting or becoming entangled in floating plastic debris (Van Dusen, 1988). Typically, birds die after consuming various small plastic particles, mistaking them for a normal meal of crustaceans or fish eggs, and turtles often mistake plastic bags and balloons for jellyfish, a prime food source. The indigestible plastic blocks the animal's intestines, causing ulcers and eventually starvation. Marine mammals such as seals and whales are also at high risk for entanglement in fishing gear and other plastic debris. Unable to move or feed normally, the entangled animals die from drowning, exhaustion and even starvation.

Some of the human-generated debris washing ashore on CACO beaches also present hazards to visitors and employees. Bottles, boards with protruding nails, light bulbs and other sharp objects, and discarded fishing nets and traps are among the many hazardous items routinely recovered from beaches.

Prior to 1988, data on the types and distribution of debris washing up at CACO and other coastal areas were generated primarily from voluntary beach clean-ups. While these data are useful for public education and media purposes, they are inadequate for quantitative assessment of the problem, developing solution strategies and evaluating the effectiveness of recent legislation that prohibits ocean dumping of plastics.

In an effort to establish a national database on the marine debris problem, the National Marine Fisheries Service (NMFS) entered into a five-year cooperative research program with the National Park Service in 1988. This venture established systematic surveys in each region of the coastal United States to assess the types, quantities and sources of human-generated debris washing ashore. CACO was one of eight NPS units participating in this national monitoring program.

Marine Debris, continued.

Research Needs.

As part of the NMFS study, marine debris found along five 1-km sections of accessible shoreline (two bay and three ocean beaches) was monitored quarterly (Manski 1990, 1991). All human-generated debris observed along these permanent survey transects was recorded and either removed or marked. Procedures followed those established by the NMFS and the Washington Support Office for the Division of Wildlife and Vegetation. This monitoring effort, which was last undertaken almost a decade ago, needs to be resumed and continued on a long-term basis in order to track changes in marine debris composition and abundance and to evaluate the effectiveness of preventative legislative measures.

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Mercury Contamination of Aquatic Environs.

Background.

Results from a joint research project conducted by the Maine Departments of Environmental Protection and Inland Fisheries and Wildlife and the University of Maine to determine the distribution and magnitude of chemical contamination of fish populations in 120 Maine lakes have revealed a high degree of mercury contamination in fish from Maine lakes, including two lakes in Acadia National Park (ACAD). Statewide, about half of the fish samples had mercury concentrations of 0.5 ppm (wet weight) or higher, and about twenty lakes contained at least one fish in the sample that exceeded 1 ppm mercury, the US Food and Drug Administration action level for mercury in fish tissue. The highest mercury levels of all fish in this study (3.4 and 2.8 ppm) were found in the two largest bass sampled. Such extremely elevated mercury levels are of concern both to human health and to the health of wildlife predators. Because mercury is the only known metal that bioconcentrates and biomagnifies in the food chain and thus has wholly harmful effects when present in fish and wildlife, the alarming levels found in Maine ecosystems with close parallels to the kettle ponds of Cape Cod National Seashore warrant a closer look at the seashore's own fish populations.

Prompted by the results of the Maine research, the United States Geological Survey -- Biological Resources Division is currently monitoring mercury contamination in five CACO kettle ponds, as well as at ACAD. Yellow perch, a favorite with CACO fishermen, is known to accumulate significant amounts of mercury in its tissue and mercury contamination has indeed been found in yellow perch from all five of the CACO study ponds. Importantly, all perch examined in recent years at the three most acidic CACO ponds (Duck, Dyer and Great Ponds in Wellfleet) have exhibited gross necrotic lesions on the head and gill covers, a syndrome termed "hole in the head" disease. The etiology of this condition is poorly described in captivity and totally unknown in the wild; however, links may exist between pond chemistry, metals mobility and the disease.

Atmospheric deposition has been implicated as a major source of mercury in freshwater lakes worldwide. Mercury is of special concern at CACO because of the proximity and abundance of upwind sources, such as Boston-area hospitals and waste incineration plants. Many of the incinerators in Massachusetts are not properly equipped to filter mercury from air emissions; an estimated 19 tons of mercury are emitted by them every year. Additionally, fish mercury content seems to be highest in lakes with soft water (that is, low in dissolved ions and in acid-neutralizing capacity) and acidic pH, conditions that are common in both ACAD lakes and CACO ponds. It is also interesting to note that sulfate concentrations are very high (median 64 mg/L) in CACO kettle ponds, a condition that may promote mercury methylation and mobilization through reactions within sulfidic sediments.

Mercury Contamination of Aquatic Environs, continued.

Research Needs.

Monitor Mercury Deposition: The ability to understand the toxicity, bioaccumulation, chemistry and transport of such a ubiquitous contaminant requires a regional approach to monitoring, as established by the National Atmospheric Deposition/Mercury Deposition Network (NADP/MDN). An offshoot of the well-established NADP National Trends Network (NADP/NTN), which has a site in Truro, the goal of the MDN is to build a database of high-quality weekly mercury deposition observations from around the continent. Placement of an additional precipitation monitor, dedicated solely to monitoring mercury deposition, at the active NADP/NTN Truro site is planned for 2002. Wet deposition samples will need to be collected on a weekly basis and analyzed by a certified environmental laboratory for total mercury. After one year, cumulative data should be used to calculate atmospheric mercury loading rates on CACO ponds and long-term monitoring, according to the mercury monitoring protocol that is currently in development, should be initiated.

Monitor Top Predator Fish Tissue in Fresh and Estuarine Environments: In order to fully evaluate the threat mercury contamination poses to both human health and wildlife resources within the seashore, the program currently being conducted by the USGS-BRD needs to be expanded to include the remaining freshwater ponds and estuaries and to monitor for additional toxins. Findings of mercury contamination should be characterized according to species as well as pond distribution, and possible links between mercury mobility and "hole in the head" disease should be explored. In order to predict and potentially protect species at risk from mercury contamination, a food chain transfer of mercury must be demonstrated, and a historical data set of trends for mercury deposition in water and/or fish determined (see below). Finally, the implementation of a long-term mercury monitoring program is necessary to assess long-term changes in mercury deposition and uptake by aquatic organisms within CACO.

Evaluate Mercury Levels in Freshwater Pond Sediments: Surface sediment samples from different locations and depths in each of the twenty CACO kettle ponds are needed in order to fully assess the distribution of mercury in Cape aquatic environments. General sediment characteristics (grain size, organic content and bulk mineralogy) should be analyzed for each sample, and concentrations of mercury, as well as other toxic metals, sulfate and sulfide, should be determined by a certified environmental laboratory. Patterns in the distribution should be documented and contoured where appropriate. Once surface distribution has been determined for all twenty ponds, two ponds should be selected for sediment coring using a Livingstone corer or similar apparatus. These cores should be analyzed for vertical changes in sediment characteristics and toxic metal content in order to evaluate historical changes in mercury and other metal accumulation in the ponds. This analysis, combined with the fish tissue monitoring described above, will serve as the basis for a risk assessment to consumers of predator fish, including birds, humans and other mammals.

Mercury Contamination of Aquatic Environs, continued.

Evaluate Mercury Pathways: Based on the sediment and fish tissue data, one pond should be selected for intensive study of food chain pathways of metal bioaccumulation. Samples of lake water, surface sediments, benthic invertebrates, zooplankton and macrophytes, as well as forage and predator fish, should be analyzed for methyl mercury and total mercury content. Organisms should be stratified by habitat: pelagic, littoral, benthic (soft and hard bottom) and macrovegetation. Relatively high body burdens should be compared with habitat type to reveal possible pathways, which should then be confirmed by gut content analysis of larger species.

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Submerged Natural Resources.

Background.

Cape Cod National Seashore contains a wide variety of marine and freshwater resources, including a heretofore largely overlooked community of submerged natural resources potentially as diverse and ecologically valuable as their well-studied aboveground counterparts. From highly productive eelgrass beds in sheltered estuaries to a complex marine network of flora and fauna in the open ocean off outer Cape shores, CACO's submerged resources are expansive and critical to the health of aquatic resources throughout the region. Massachusetts has designated all coastal waters surrounding the seashore as an ocean sanctuary (Mitchell and Soukup, 1980) and the seashore's boundary extends ¼ mile into nearshore coastal waters, yet its submerged natural resources have never been comprehensively inventoried. Given the potential for sea level rise accelerated by global climate change and the continued subsequent submergence of the CACO coastline, such baseline data on today's submerged resources are especially critical to our understanding of long-term ecological change in submerged systems.

Research Needs.

Convene Workshop: A workshop to address the present state of knowledge regarding submerged natural resources within the seashore is envisioned as the first step in a long-term effort to inventory and monitor CACO's underwater ecosystems. Building on the 1994 University of Rhode Island forum on CACO's submerged estuarine systems (Beatty et al., 1994), this workshop should expand in scope to include the park's purely marine and freshwater underwater communities. Participants in the workshop should include scientists, commercial and public users of submerged resources and representatives of the responsible management agencies. The forum should focus on reviewing available information sources and on identifying the presence of important species and habitats by ecological, regulatory and economic criteria. Preliminary evaluations of their location, controlling processes, seasonal changes and threats, both human and natural, should be made. Data collection methods should be addressed, including field and remotely sensed data, along with specific indicator species, habitats and processes on which to focus. Specific attention should also be given to the methodologies whereby any data, existing or yet to be gathered, can be incorporated into CACO's Geographic Information System.

Submerged Natural Resources, continued.

Design Monitoring Protocol: Following the workshop, a detailed protocol for inventorying CACO's submerged resources must be developed. Based on criteria established at the workshop and augmented by the investigator and CACO staff, the protocol should select and prioritize species and/or habitats to be studied, and identify data collection methods, seasonal modifications and indicators for each one. The protocol should further provide for investigation of submerged habitats with respect to physical structure, species composition, density (for select biotic groups), ecological quality and function. Threats to sensitive habitats and species also need to be identified and described.

Implement Monitoring: Upon completion of the protocol design, a prototype inventory of submerged resources should be conducted. Based on the plan, the actual inventory program should begin by focusing on a particular species and/or habitat type and gradually expand in breadth. The prototype inventory should include CACO staff as data collectors and logistical support in order to simplify the transition from prototype to institutionalized inventory. Continued monitoring according to these final inventory standards is then needed on a long-term basis.

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Wetland Plant Species.

Background.

Between 1984 and 1987, the distribution of rare plants in Cape Cod National Seashore (CACO) was mapped and, of all the habitats surveyed, pond shores emerged as the most threatened rare plant habitat in the seashore (LeBlond, 1990). Indeed, human pressures on all freshwater and saltwater wetlands in CACO may pose a substantial threat to wetland plant species occurring on or adjacent to wetland shores. Nutrient runoff from household septic systems and the resulting accelerated growth of aquatic plants is a critical concern. Municipal groundwater withdrawal plans and the subsequent lowering of the water table and changes in nutrient availability could alter the plant species composition of some CACO wetlands, thus allowing for increased encroachment of upland plants (Cortell, 1983, Roman et al., 1997). Foot traffic, flora and fauna collecting, shellfishing and other recreational uses of wetland areas also have an impact on wetland plant communities. While inventories have been completed that identify wetland plant species within CACO (Cortell, 1983; LeBlond, 1990; Patterson, 1988), quantitative monitoring to document the changes in species communities brought about by human impacts has only been implemented at five kettle ponds (Roman et al. 2001). Without field monitoring to document such changes in all of CACO's wetland plant species communities, CACO managers will lack quantitative data to support potential wetland protection measures.

Research Needs.

Map Inventory Data: Existing inventory and monitoring plots need to be identified, located and mapped on CACO's Geographic Information System.

Monitor Wetland Plant Communities: The wetland inventory and monitoring plots that currently exist within CACO use a variety of different classification and sampling systems. Development of a consistent re-sampling and monitoring protocol is planned for 2002; wetland areas without established monitoring plots or quantitative sampling data will be identified in priority order and consistent standards for classification and sampling of wetland plant species will be set. Once this monitoring methodology has been developed, long-term monitoring is necessary in order to track changes in wetland plant communities within the seashore.

Wetland Plant Species, continued.

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